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# JUDGING INVASIVENESS UNDER SCIENTIFIC UNCERTAINTY: VALUE ORIENTATIONS AND REASONING PATTERNS OF PRE-SERVICE BIOLOGY TEACHERS ON THE GOLDEN APPLE SNAIL

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**Abstract.** *In the Anthropocene era, science educators must equip students to reason through uncertainty and navigate value-laden environmental dilemmas. This study aimed to examine how pre-service biology teachers make value-based decisions when facing scientific uncertainty, using the case of the golden apple snail (Pomacea canaliculata) and its designation as an invasive species. Drawing on the framework of post-normal science and environmental ethics, a scenario-based mixed-methods survey was conducted with 191 participants across five universities in South Korea. Quantitative results showed that 69.1% of respondents supported the designation, typically adopting ecocentric and precautionary perspectives, while 30.9% opposed it, citing anthropocentric pragmatism and techno-optimism. Qualitative analysis revealed confirmation bias and temporal framing patterns, with participants selectively interpreting evidence in ways consistent with their prior value orientations. These findings highlighted the importance of fostering uncertainty literacy, critical thinking, and ethical reasoning in science teacher education. The study offers international relevance by addressing how future educators construct environmental judgments under uncertainty, with implications for curriculum design across diverse socio-ecological contexts.*

**Keywords:** *invasive species, decision making, pre-service teachers, scientific uncertainty, value orientation*

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## Introduction

In the Anthropocene era, the interlinked crises of climate change, biodiversity loss, and invasive species have become defining challenges for ecosystems and human societies. These unprecedented conditions demand new ways of thinking about science education and environmental decision-making, as emphasized by previous research (Crutzen & Stoermer, 2000; Lee & Park, 2024; Steffen et al., 2015). These challenges are further complicated by the volatility, uncertainty, complexity, and ambiguity (VUCA) of the conditions that define our era, where scientific knowledge is often incomplete, evidence is contested, and the consequences of decisions are far-reaching and unpredictable (Funtowicz & Ravetz, 1993; Wals & Jickling, 2002). In this context, the role of science education, and the preparation of future science teachers in particular, has become increasingly significant, as teachers are called upon to foster not only scientific literacy but also the ability to reason through uncertainty and navigate value-laden dilemmas (Jeong et al., 2021; Sadler, 2004; Yavuzkaya et al., 2024; Zeidler et al., 2005).

The golden apple snail (*Pomacea canaliculata*) provides a compelling case study examining how pre-service biology teachers approach scientific uncertainty and value conflict. Introduced in South Korea in 1983 as a biocontrol agent for eco-friendly rice farming, this snail species initially contributed to reducing herbicide use and has been widely adopted in sustainable agriculture. However, their rapid reproduction and adaptability have led to their designation by the International Union for Conservation of Nature as one of the 100 most invasive species worldwide, causing significant ecological and agricultural concerns in several countries (Bang & Cho, 2008; Lowe et al., 2000). Climate change further complicates this situation because rising



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winter temperatures may enable snails to survive and proliferate in new regions, increasing the risk of ecological disruption (IPCC, 2021; Steffen et al., 2015).

Despite the global relevance of invasive species management and the growing importance of uncertainty reasoning in science education, few studies have explored how future educators make value-laden decisions in contexts characterized by ambiguous or conflicting evidence. Empirical research on pre-service biology teachers' reasoning patterns and value orientations under scientific uncertainty remains limited, particularly in the East Asian context.

This gap is significant, given that their personal frameworks of reasoning and ethics may influence how they teach complex environmental issues.

Socioscientific issues such as the designation of invasive species are inherently complex and controversial, requiring decision makers to weigh scientific evidence, ethical considerations, and the interests of diverse stakeholders (Sadler, 2004; Zeidler et al., 2005). In such contexts, scientific knowledge alone is often insufficient for decision-making; individuals must integrate empirical data with value judgments, risk perceptions, and societal priorities (Funtowicz & Ravetz, 1993; Kortenkamp & Moore, 2001). Studies have shown that the reasoning of pre-service teachers regarding socioscientific issues is influenced by their understanding of science and ethical orientations, worldviews, and experiences (Jickling & Wals, 2008; Sadler & Zeidler, 2005). For example, some may adopt an ecocentric perspective, emphasizing the intrinsic value of nature and the precautionary principle, whereas others may prioritize human utility, technological optimism, or pragmatic solutions to environmental problems (Dryzek, 2013; Naess, 1973).

Furthermore, the lack of explicit instruction in uncertainty reasoning, critical thinking, and ethical deliberation in many teacher education programs highlights the urgent need for curriculum reforms. By examining how pre-service biology teachers interpret evidence and negotiate value-laden decisions under real-world ecological uncertainty, this study provides insight into how teacher education can evolve to better prepare future educators.

Despite the recognized importance of uncertain reasoning and value negotiations in science education, many teacher preparation programmes continue to focus on transmitting established knowledge and scientific consensus, neglecting the skills needed to address ambiguities, controversies, and ethical complexities (Halpern, 2014; Lotz-Sisitka et al., 2015). This gap is particularly problematic in the Anthropocene, where environmental issues are rarely clear-cut and often require balancing competing values and uncertain outcomes (Crutzen & Stoermer, 2000; Steffen et al., 2015). As future educators, pre-service biology teachers must be equipped to teach scientific facts and guide students through critical reflection, ethical deliberation, and informed decision-making in the face of uncertainties (Wals & Jickling, 2002; Zeidler et al., 2005).

This need was addressed by examining how Korean pre-service biology teachers evaluate ambiguous ecological and agricultural information concerning the golden apple snail, and how distinct ethical and cognitive orientations influence their decisions. By foregrounding both the international relevance of invasive species issues and the under-examined dimension of uncertainty reasoning in teacher education, this study contributes to global discussions on science pedagogy in complex socio-ecological contexts. Unlike previous studies focusing primarily on content knowledge or socioscientific argumentation, this study uniquely integrated ecological uncertainty, ethical reasoning, and cognitive framing into teacher education research.

## Theoretical Framework

### *Socioscientific Issues and Post-Normal Science*

Socioscientific issues are complex, real-world problems that require individuals to integrate scientific evidence with ethical reasoning and social values, often under conditions of uncertainty and controversy (Sadler, 2004; Zeidler et al., 2005). Post-normal science involves situations in which facts are uncertain, values are disputed, and decisions are urgent—characteristics common to contemporary environmental challenges, such as invasive species management and climate change adaptation (Funtowicz & Ravetz, 1993). In this context, science education must move beyond the transmission of settled knowledge to foster skills for navigating ambiguity, deliberating values, and making informed decisions in the face of incomplete evidence (Jickling & Wals, 2008; Wals & Jickling, 2002).

This framework has been increasingly applied in science education to examine how learners and teachers respond to ill-structured problems lacking clear solutions (Lotz-Sisitka et al., 2015; Zeidler et al., 2005). Sadler and Zeidler (2005) demonstrated that post-normal conditions elicit diverse informal reasoning strategies among students. However, relatively few studies have investigated how pre-service teachers, as future decision facilitators, engage in post-normal dilemmas in environmental decision-making. This study is built on post-normal science


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by focusing on how candidate teachers interpret and respond to value-laden ecological uncertainty in the case of the golden apple snail.

### *Environmental Ethics and Value Orientations*

Ethical frameworks deeply influence environmental decision-making, particularly the tension between ecocentrism and anthropocentrism (Kortenkamp & Moore, 2001; Naess, 1973). Ecocentric perspectives emphasize the intrinsic value of nature and the integrity of ecosystems, advocating the precautionary principle when faced with ecological uncertainty (O'Riordan & Cameron, 1994). In contrast, anthropocentric or pragmatic approaches prioritize human utility, technological solutions, and adaptive management, often favoring innovation and risk-taking over precautions (Dryzek, 2013). These value orientations influence how teachers and students perceive scientific uncertainty and make decisions concerning environmental management, as evident in debates over the invasive status of species such as the golden apple snail (Sadler & Zeidler, 2005).

This duality in value orientation has been observed in environmental philosophy and science education research. Zeidler et al. (2005) emphasized that value-based reasoning is central to socioscientific decision making, particularly when learners are confronted with ethically ambiguous information. Recent studies have investigated how students and teachers adopt different ethical stances depending on contextual framing (Sadler, 2004; Yavuzkaya et al., 2024). However, few studies have examined how these orientations manifest in the reasoning of pre-service biology teachers under ecological uncertainty.

### *Patterns in Information Processing and Uncertainty Reasoning*

When individuals encounter ambiguous or controversial information, their prior beliefs and values often influence how they interpret and recall the evidence (Klayman & Ha, 1987; Mercier & Sperber, 2011). In environmental issues, people may focus on data supporting their initial stance while downplaying or reinterpreting contrary evidence, leading to persistent differences in judgment even when presented with the same facts (Sadler, 2004; Halpern, 2014). This tendency can reinforce polarization and hinder balanced deliberation in environmental controversies. Addressing these information processing patterns is a key challenge in science education and requires explicit instruction in critical thinking, argumentation, and metacognitive reflection (Halpern, 2014; Lotz-Sisitka et al., 2015). These skills need to be integrated into teacher education so that educators are equipped and prepared to help students adopt nuanced, reflective, and participatory approaches to science learning in the Anthropocene era (Wals & Jickling, 2002).

Confirmation bias has been identified as a key barrier in fostering critical engagement on controversial issues in science education. For instance, Halpern (2014) argued that without explicit metacognitive training, learners process socioscientific information in ways that reaffirm their preexisting positions. This study built on such insights by analyzing how pre-service teachers interpret the same ecological and agricultural claims differently depending on their value orientations. It revealed patterns of selective attention, reinterpretation, and temporal framing.

### *Research Aim and Research Questions*

This study examined how pre-service biology teachers make value-based decisions under scientific uncertainty in the context of environmental controversy. Specifically, it examined how they justify their support for or opposition to designating the golden apple snail (*P. canaliculata*) as an invasive species and how ethical orientations and information processing patterns influence their reasoning. Grounded in the framework of post-normal science and socioscientific issues, this study sought to reveal the interplay between scientific evidence, personal values, and cognitive strategies that influence environmental decisions among future science educators.

The following research questions were formulated to address this aim:

> RQ1. How do pre-service biology teachers justify their support for or opposition to designating the golden apple snail as an invasive species under scientific uncertainty, and what value orientations characterize these decisions?
>
> RQ2. What reasoning and evidence interpretation patterns emerge when pre-service biology teachers encounter conflicting ecological and agricultural information on golden apple snails?


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## Research Methodology

### *Design and Context*

This study used an exploratory sequential mixed-methods design (Creswell & Clark, 2017), combining quantitative and qualitative approaches, to examine how pre-service biology teachers reason through scientific uncertainty. It was conducted during the spring semester of 2023 at five universities in South Korea.

Grounded in the frameworks of socioscientific issues (Zeidler et al., 2005) and post-normal science (Funtowicz & Ravetz, 1993), the study focused on teachers' decision-making processes in the face of ambiguous ecological and agricultural information.

### *Participants*

One hundred ninety-one pre-service biology teachers from five universities in South Korea were enrolled in the study. The sample size was not predetermined by statistical calculation; instead, it reflected the full number of students who were available and consented to participate across the five universities at the time of data collection. The participants ranged from first- to fourth-year undergraduate students majoring in biology education, comprising 67 males (35.1%), 123 females (64.4%), and one participant who did not disclose gender. This individual was excluded from gender-based statistical analyses. Because the study included students from multiple regions and all academic levels, the sample ensured contextual diversity and representativeness within the scope of Korean biology teacher education programs. Participants were informed of the study's aims, ethical considerations, and data confidentiality and voluntarily provided informed consent. This study was conducted in accordance with the institutional ethical guidelines.

### *Instruments*

The participants were presented with a scenario[Appendix 1] describing golden apple snails' ecological and agricultural impacts, including conflicting expert opinions and climate change projections. The researcher carefully constructed a scenario based on diverse online news articles, expert commentaries, and public reports on using golden apple snails in Korean agriculture. These sources were selected to reflect the socio-political and environmental contexts of *P. canaliculata* management in South Korea. Foundational insights from prior research on this species' ecological risks and global invasive status were also incorporated (Bang & Cho, 2008; Lowe et al., 2000). The scenario, a fictionalized yet realistic dialogue between two ecologists with opposing views, was designed to simulate the value-laden and scientifically uncertain debates that characterize real-world socioscientific issues.

The content was based on controversies observed in South Korea regarding the ecological risks and agricultural benefits of introducing the golden apple snail, enhancing the instrument's contextual and ecological validity. The structured questionnaire consisted of the following questions.

- A binary choice on whether to designate the snail as an invasive species.
- Open-ended questions probing the rationale for their decision.
- Items asking which information most influenced their judgment.
- Requests for detailed justification of their stance.

Two science education experts and an environmental scientist reviewed the scenario and questionnaire to ensure content validity. Their feedback was used to revise potentially ambiguous statements and ensure alignment with the theoretical constructs addressed in this study.

### *Data Collection and Analysis*

Data were collected during scheduled class sessions in the spring of 2023. Following this, 191 pre-service biology teachers read a detailed explanation of the purpose of the study and provided voluntary, informed consent for participation. The average response time was 25–30 minutes, allowing participants to reflect deeply on the invasive species scenario (Creswell & Clark, 2017). Quantitative responses were analyzed using descriptive statistics and cross-tabulations to identify overall decision trends and demographic patterns according to sex and academic year (Field, 2013). Chi-square tests were conducted to determine whether statistically significant differences existed between the decision outcomes and participant characteristics.


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Qualitative data were analyzed using thematic analysis based on a constant comparative method (Braun & Clarke, 2006). Two researchers independently read all open-ended responses and extracted discrete meaning units based on recurring patterns in language and reasoning. Through iterative comparisons and discussions, emergent codes were developed and refined until a consensus was reached.

These codes were then grouped into broader themes, including ecosystem guardianship, future risk prevention, eco-pragmatism, and techno-optimism, which were mapped onto theoretical constructs such as the precautionary principle and the ecocentrism–anthropocentrism spectrum (Kortenkamp & Moore, 2001). This analytical process aimed to preserve the integrity of the participants' voices while enhancing the credibility and trustworthiness of the findings.

## Research Results

### *Quantitative Results*

Of the 191 pre-service biology teachers, 132 (69.1%) supported the designation of the golden apple snail as an invasive species, and 59 (30.9%) opposed it. Chi-square tests revealed no statistically significant associations between designation decisions and gender ($\chi^2(1) = .31$, $p = .58$) or academic year ($\chi^2(3) = 1.95$, $p = .58$). This suggested that demographic variables such as gender and academic level were not significantly associated with participants' decisions.

Among the 132 participants, 86 (65.2%) expressed ecosystem guardianship, 23 (17.4%) expressed agricultural realism, 15 (11.4%) expressed future risk prevention, 5 (3.8%) expressed integrated concerns, and 3 (2.3%) expressed scientific principles. Among the 59 anti-designation participants, 32 (54.2%) expressed eco-pragmatism, 13 (22.0%) expressed techno-optimism, 9 (15.3%) expressed cautious synthesis, 3 (5.1%) expressed biodiversity enhancement, and 2 (3.4%) expressed status-quo advocacy.

### *Qualitative Results*

#### Value Orientations in Reasoning

Qualitative analysis identified distinct reasoning patterns associated with the participants' value orientations. The pro-designation group predominantly invoked ecocentric and precautionary rationales. Participants emphasized the value of native species, the unpredictability of ecological impacts, and the need to prevent irreversible harm. They also cited the potential risks of ecosystem disruption and long-term invasiveness.

Within the pro-designation group, value orientations included ecosystem guardianship, future risk prevention, scientific principles, agricultural realism, and integrated concerns. For instance, one participant noted, "If winters get warmer, snail populations will explode, threatening native ecosystems," which reflects a long-term ecological concern.

In contrast, the anti-designation group emphasized the benefits of using snails in agriculture and the manageability of potential risks. Their value orientations include eco-pragmatism, techno-optimism, biodiversity enhancement, status quo advocacy, and cautious synthesis. A representative response reflecting eco-pragmatism was, "Using snails reduces pollution and boosts biodiversity." Table 1 presents the value orientations and representative responses related to participants' decisions regarding the invasive status of golden apple snails.

**Table 1**
*Distribution of Value Orientations Among Pre-Service Biology Teachers Regarding the Invasive Species Designation*

| Value orientation | Pro-designation | Anti-designation | Representative response |
|---|---|---|---|
| Ecosystem guardianship | 86 (65.2) | N/A | "If winters get warmer, snail populations will explode, threatening native ecosystems." |
| Future risk prevention | 15 (11.4) | N/A | "Climate change may enable snail proliferation, so early action is essential." |


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| Value orientation | Pro-designation | Anti-designation | Representative response |
|---|---|---|---|
| Scientific principlism | 3 (2.3) | N/A | "Global IUCN guidelines list this species as invasive, so precaution is warranted." |
| Agricultural realism | 23 (17.4) | N/A | "They devour rice seedlings faster than we can remove them." |
| Integrated concerns | 5 (3.8) | N/A | "Weighing ecosystem integrity and farm productivity led me to support the designation." |
| Eco-pragmatism | N/A | 32 (54.2) | "Using snails reduces pollution and boosts biodiversity." |
| Techno-optimism | N/A | 13 (22.0) | "With proper management, harm is minimal." |
| Biodiversity enhancement | N/A | 3 (5.1) | "New species appeared in snail-infested fields, increasing diversity." |
| Status quo advocacy | N/A | 2 (3.4) | "No major harm has been documented, so current practices should continue." |
| Cautious synthesis | N/A | 9 (15.3) | "Adaptive management with ongoing research offers a middle path." |
| Total | 132 (100%) | 59 (100%) | |

*Notes:* Percentages reflect orientation-specific counts among proponents (first five) or opponents (last five) of the invasive species designation. Representative responses were drawn from survey data. IUCN: International Union for the Conservation of Nature. $n = 191$, values reflect frequency and percentage.

## Cognitive Reasoning Patterns

Confirmation bias was commonly observed; participants often interpreted the same information (e.g., increased biodiversity) in ways that supported their stance. For instance, pro-designation participants viewed short-term biodiversity gains as temporary and outweighed long-term risks, whereas anti-designation participants viewed the same data as evidence of compatibility.

These interpretations aligned with the participants' value orientations. Eco-pragmatic or techno-optimistic participants focused on short-term benefits, whereas those aligned with ecosystem guardianship or future risk prevention emphasized the importance of precaution.

Temporal framing also played a significant role. Pro-designation participants emphasized long-term ecological risks and responsibilities, whereas anti-designation participants highlighted immediate benefits and feasibility. These reasoning patterns were classified based on the participants' references to timing and interpretation.

Table 2 summarizes the cognitive reasoning patterns identified in the participants' responses, categorized by confirmation bias and temporal framing subtypes.

**Table 2**
*Cognitive Reasoning Patterns Used by Participants in Interpreting Scientific Uncertainty*

| Cognitive pattern | Subtype | Description | Example response |
|---|---|---|---|
| Confirmation bias | Selective attention | Focusing only on evidence that supports one's prior belief while downplaying or ignoring contradictory information | "Short-term diversity gains are misleading anomalies overshadowed by long-term species loss." |
| | Counterevidence discount | Minimizing or reframing disconfirmation data to align with one's existing viewpoint | "Managed snail populations offer agricultural benefits without causing lasting ecological harm." |
| | Reinterpretation | Recasting identical information to fit one's original position, despite neutral or opposing contexts | "Increased biodiversity proves ecological compatibility, not invasion." |


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| | | | |
|---|---|---|---|
| Temporal framing | Future-risk emphasis | Emphasizing long-term, intergenerational risks to justify precautionary or protective measures | "If warming continues, uncontrolled snail proliferation will irreversibly alter habitats for future generations." |
| | Present-benefit emphasis | Highlighting immediate advantages and feasibility to support continuation of current practices | "Today's gains in crop productivity and reduced herbicide use justify ongoing snail management rather than premature restriction." |
| | Balanced-time framing | Integrating both near-term benefits and long-term risks to propose moderated, adaptive solutions | "Adaptive management now and further studies later offer a balanced approach to address both immediate needs and future uncertainties." |

## Discussion

Pre-service biology teachers who supported the invasive species designation of the golden apple snail often prioritized ecological integrity and the intrinsic value of native species, reflecting an ecocentric worldview (Funtowicz & Ravetz, 1993). They argued that uncertain long-term ecological impacts such as disrupted food webs and declining biodiversity warrant precautionary measures to prevent irreversible harm (O'Riordan & Cameron, 1994). This group tended to perceive ecological risk through a future-oriented lens, aligning with the precautionary principle, particularly relevant in post-normal science contexts characterized by complexity, uncertainty, and value-laden decisions (Funtowicz & Ravetz, 1993). In contrast, those opposing the designation have frequently adopted anthropocentric and pragmatic rationales, emphasizing the role of snails in reducing herbicide use and bolstering short-term agricultural productivity (Kortenkamp & Moore, 2001). This reflects a present-focused, utility-based assessment of ecological intervention and illustrates a techno-optimistic perspective, in line with Dryzek's (2013) characterization of pragmatic environmentalism. This dichotomy mirrors broader environmental ethics debates in which ecocentric and anthropocentric frameworks offer competing prescriptions for managing ecological uncertainty (Naess, 1973).

The precautionary principle advocates for preventive action when scientific uncertainty surrounds potentially serious environmental harm (O'Riordan & Cameron, 1994). Pro-designation teachers invoked this principle to justify early intervention, citing climate change projections that could enable snails to invade new regions (IPCC, 2021). They argue that delaying action until conclusive evidence emerges risks irreversible ecological damage, which is consistent with post-normal scientific thinking in the context of high uncertainty and contested value (Funtowicz & Ravetz, 1993). However, opponents have questioned the adequacy of the precaution-based approach, expressing confidence in adaptive management tactics to control snail populations without resorting to invasive species designations (Dryzek, 2013). This contrast demonstrated how differing environmental ethics and attitudes toward uncertainty can lead to divergent policy preferences, underscoring the importance of incorporating precautionary and adaptive frameworks in science education (Zeidler et al., 2005). This discussion further reinforces the answer to RQ1 by illustrating how contrasting ethical perspectives (precautionary vs. adaptive) shaped participants' judgments.

Teachers' interpretations of ambiguous biodiversity data revealed a tendency toward confirmation bias, in that individuals tended to favor evidence that supported their existing viewpoints (Klayman & Ha, 1987). The pro-designation respondents viewed short-term increases in biodiversity as transient anomalies that long-term declines in native species would overshadow. In contrast, the anti-designation proponents considered the same data proof of ecological compatibility (Sadler & Zeidler, 2005). These contrasting interpretations of identical data underscore how deeply values influence cognitive evaluations of evidence, a pattern consistent with prior research emphasizing the value-ladenness of socioscientific reasoning (Sadler & Zeidler, 2005). This selective interpretation underscores the challenge of fostering balanced deliberation in environmental controversies and highlights the need for metacognitive strategies to help teachers and students recognize and mitigate bias (Halpern, 2014). These findings respond to RQ2, which examined what reasoning patterns emerge when pre-service teachers interpret conflicting information on golden apple snails.

Temporal framing also played a significant role, with supporters of the invasive species designation emphasizing long-term risks and intergenerational responsibility, while opponents prioritized immediate agricultural benefits and feasibility (Ojala, 2012; Slovic, 1987). Such temporal framing suggested that the time horizon is a critical lens through which ecological risk is perceived and acted upon and underscores the pedagogical value of explicitly


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addressing how different timeframes influence environmental decision-making (Ojala, 2012). This emphasis on confirmation bias and temporal framing directly addresses RQ2, highlighting the cognitive processes underlying participants' reasoning under uncertainty.

The observed diversity of value orientations and reasoning patterns highlighted the importance of integrating uncertainty literacy, ethical reasoning, and critical thinking into science teacher education programmes (Jickling & Wals, 2008). Teacher preparation should include case-based learning concerning socioscientific issues, emphasizing the nature of scientific uncertainty and the precautionary principle, and teaching adaptive management frameworks to address techno-optimistic perspectives (Zeidler et al., 2005). Structured argumentation exercises can help pre-service teachers recognize and counter confirmation bias, fostering metacognitive reflection and balanced deliberation (Mercier & Sperber, 2011). Furthermore, role-play simulations of stakeholder debates can cultivate empathy and broaden ethical horizons, preparing educators to guide students through complex environmental decisions (Lotz-Sisitka et al., 2015).

Teacher education curricula should integrate explicit training modules on value negotiation, evidence appraisal, and uncertainty framing to translate these insights into practice. Incorporating Toulmin-based argument mapping, reflective journaling, and simulation-based decision-making tasks can support the development of adaptive reasoning under ambiguous conditions. By equipping future educators with such tools and habits, science education can move beyond content delivery to cultivate reflective, ethically grounded professionals capable of engaging with the socio-ecological challenges of the Anthropocene.

## Conclusions and Implications

This study demonstrated that, as future science educators, pre-service biology teachers brought diverse value orientations and reasoning strategies to their judgments when confronted with scientific uncertainty regarding the designation of the golden apple snail as an invasive species. Their decisions reflected multiple perspectives, including ecocentric and anthropocentric orientations, precautionary thinking and techno-optimism, and temporal considerations prioritizing long-term ecological risks or immediate agricultural benefits. Selective information processing and confirmation bias were prevalent, with participants often interpreting ambiguous or conflicting evidence to reinforce their initial value positions, reflecting broader patterns of value-laden reasoning commonly observed in socioscientific decision-making.

These findings highlight the need for science teachers to move beyond knowledge transmission and explicitly foster uncertainty literacy, critical thinking, and ethical deliberation.

Although this study was conducted in South Korea, its implications resonate with the global debates on invasive species management under scientific uncertainty. It offers valuable insights into how future science teachers construct meaning and make decisions in ethically and ecologically complex contexts. The study also contributes to broader discussions in science education regarding socioscientific reasoning, teacher beliefs, and sustainability-oriented pedagogy, which are increasingly emphasized in recent scholarship and educational reform agendas.

Teacher preparation should incorporate practical tools such as scenario-based simulations, argument mapping, and structured ethical debates to help pre-service teachers engage with real-world dilemmas and practice value negotiations. Reflective journaling and role-playing can strengthen metacognitive awareness, enabling teachers to guide students through ethically complex classroom decisions. By integrating such approaches, science education can cultivate reflective and ethically responsible professionals prepared to navigate the socio-ecological challenges of the Anthropocene.

This study has several limitations. First, a scenario-based survey, useful for eliciting structured reasoning, may not fully capture how pre-service teachers would make decisions in real-world contexts, such as classrooms, curricula, or public policy discussions. A social desirability bias may have influenced participants, potentially framing their justifications in ways they believed were ethically or environmentally acceptable.

Second, although qualitative coding was rigorously performed with the researchers reaching a consensus, the thematic mapping process inherently involved interpretive judgments that may have influenced how certain responses were classified under specific value orientations. While methodologically valid, this interpretive nature calls for caution when generalizing typologies beyond this study.

Third, the participant sample consisted solely of biology students from South Korea. The study's findings may not directly apply to different national or disciplinary contexts despite offering insights into culturally relevant environmental issues.


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Future research should explore how sustained engagement with socioscientific controversies influences the development of ethical reasoning and tolerance for uncertainty among pre-service teachers. Longitudinal studies could examine how targeted instructional interventions, such as ethics modules or adaptive management tasks, shape value orientations and decision-making strategies. In addition, cross-cultural comparisons would be valuable for understanding how educators in different educational systems draw on distinct ethical or epistemic frameworks when addressing environmental uncertainty.

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**Declaration of Interest**

The authors declare no competing interest.

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**Appendix 1.**

**Dialogue Used in the Survey: Debate between Ecologists on the Golden Apple Snail**

**The following is a fictional dialogue between ecologists Dr. Kim and Dr. Lee regarding the designation of the golden apple snail (currently listed as an "ecological risk species" in Korea) as an invasive alien species. Please read it carefully and respond to the questions below.**

Dr. Kim: One of our country's most significant challenges in rice farming is weeds. They grow endlessly everywhere and reduce the rice yield. However, using herbicides to remove weeds can cause environmental pollution, so we need to be cautious. That is why, since the 1990s, we have been using golden apple snails to eliminate weeds. They are very efficient—capable of removing up to 98% of all weeds. Golden apple snails make eco-friendly farming possible by increasing rice yield without causing environmental damage.

Dr. Lee: But golden apple snails are a species introduced from tropical regions. They reproduce rapidly and have a broad appetite, eating weeds, water parsley, and even native snails. They have been designated as an "ecological risk species" in Korea. The International Union for Conservation of Nature even listed them among the world's 100 most invasive alien species.

Dr. Kim: However, golden apple snails cannot survive winter in Korea. If temperatures drop below −3 °C for just three days, they die. According to a local government report, the golden apple snails' population decreased significantly because they could not endure winter, and no single case of damage caused by them was reported. Because Korea has cold winters, it is not as suitable for golden apple snails as other countries.

Dr. Lee: Due to climate change, winter temperatures in southern Korea have become warmer than average. There have been cases in the south where golden apple snails survive winter. This phenomenon gradually spread northward. As a result, some local governments have set up dedicated periods after the rice harvest to collect snails. If they survive winter, they can harm young rice plants by nibbling during the spring planting season.

Dr. Kim, an expert in eco-friendly agriculture, has stated that if appropriately managed, golden apple snails will not pose a significant threat to the ecosystem. Farmer Kim ○○, who has been using golden apple snails for over 10 years, also mentioned that he has experienced almost no problems. In contrast, since herbicides are not used, organisms such as tadpole shrimp have reappeared, and biodiversity has increased. Golden apple snails are inexpensive and enable environmentally friendly rice farming. As of 2018, 88.9% of the eco-friendly rice farms in Korea have been using golden apple snails. Therefore, their designation as invasive species would significantly harm eco-friendly farming practices.

Dr. Lee: Golden apple snails damage other crops and ecosystems and harm rice farming by feeding on young rice shoots. Mr. Park, a village head in △△ the Village, lamented that just two snails ate an entire rice plant within an hour. In 2020, approximately 17% of the area's total farmland (approximately 600 soccer fields) was damaged by golden apple snails. Countries such as Taiwan, Japan, and Vietnam have banned snail farming. We cannot predict the type of damage that this species might cause to Korean ecosystems in the future. Therefore, golden apple snails must be considered invasive to prevent future large-scale damage.


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